Mobility-based Strategies for Energy Restoration in Wireless Sensor Networks

Elio Velazquez
School of Computer Science
Carleton University, Canada
Email: evelazqu@scs.carleton.ca

Nicola Santoro
School of computer Science
Carleton University, Canada
Email: santoro@scs.carleton.ca

***Abstract*— Energy management has become one of the main hurdles in the quest for autonomous and reliable Wireless Sensor Networks (WSN). This papers examines the emerging problem of increasing network availability by recharging, replacing or redeploying "depleted" sensors with the help of mobile entities. When mobility becomes a sensor's attribute and service stations are static, we propose passive vs. pro-active approaches to energy redistribution and restoration. In particular, for pro-active approaches, we study the mobility strategies and underlying topologies that guarantee a successful sensor recharge. The experimental results so far show that taking our novel pro-active approach to energy redistribution and network fatigue outperforms passive strategies. The proposed closest-first swapping-based mobility strategy provides the best overall performance among all the pro-active approaches studied and the proposed Compass Directed Unit Graph provides an efficient and flexible underlying topology to achieve energy equilibrium.**

I. INTRODUCTION

A. The Framework

Energy management and, in particular, energy restoration are one of the main challenges to achieve an autonomous and reliable Wireless Sensor Network (WSN). The ultimate goal of a sensor network is to achieve accurate sensing and maximize lifetime while maintaining an acceptable level of coverage. However, in any wireless sensor deployment, eventually the sensors will deplete the batteries and loss of coverage would occur. A simple solution to overcome this problem is to deploy more sensors. This is sometimes not possible, environmentally friendly or perhaps economically sensible. Another possible alternative would be to redeploy the remaining sensors to compensate for the loss of coverage. While this approach would extent the network lifetime, the remaining sensors will eventually die and the loss of coverage will be inevitable.

More creative approaches to cope with an eventual loss of coverage attempt to extract energy from the environment in order to extend network lifetime [20], [21]. Others explore the use of mobile entities (robots, actuators, service stations) in conjunction with clustering techniques as a means of saving energy and coordinating sensors for data gathering, aggregation and network repair [16], [29], [13], [23].

In general, energy management strategies can be categorized in two main groups: cluster based approaches (e.g [19], [14], [34], [10]) or mobility based approaches (e.g. [17], [32], [15], [31], [13], [22]). In this paper we follow precisely the second approach. The crucial points of a mobility-based approach are 1) which network elements (sensors or service stations) will have mobility capabilities and 2) according to what policies and strategies should sensors obtain the required services.

B. The Problem

Recent advances in sensor technology, batteries and recharging mechanisms have made possible the idea of recharging wireless devices by either docking them to recharging stations or by transmitting power at short distances using electromagnetic induction or resonance of electromagnetic waves (e.g. [17], [9], [1], [2]). In this work we study the scenario where mobility capabilities are added to the sensors and static service/recharge facilities are deployed throughout the sensing area. In this scenario, the responsibility for maintaining the overall health of the network is shifted to the sensor side, whereas the service facilities play a more passive role. The service facilities are equipped with a fixed number of recharging sockets and the sensors should coordinate their actions to make an efficient use of this shared resource. In our scenario we use the abstract concept of "recharging socket" as mechanism used by service stations to deliver energy to the sensors. The mechanisms used for the actual transfer of energy (wireless means or physically docking) depend on the technology chosen and is not within the scope of our problem. Therefore, the abstract term "number of sockets" refers only to the capacity to serve multiple sensors simultaneously.

Under normal circumstances and overall energy levels at an acceptable state, the problem is: Should the sensors act while their batteries are still fully operational or later, when their batteries reach a critical level (close to depletion)? This work attempts to provide an answer to this question by addressing the problem of network fatigue from a passive and a pro-active perspective.

The idea of dynamic redistribution of the network, when it is still in a healthy state, seems attractive. By exchanging positions with other sensors, lower energy sensors can get closer to the service stations and thus get "front seats" for when their time comes to make a trip to the service station. However, this pro-active behaviour introduces another problem. The sensors need to communicate and coordinate their actions in order to achieve a common goal. This common goal should be achieved with local information only. This extra need for coordination comes at a cost which should not overwhelm the entire system, preventing it from outperforming a passive approach. Furthermore, sensors should coordinate their moves in a loop free manner so the intended destination (service station) is reached in a finite number of moves or steps. The ultimate goal of a pro-active approach is to reach a state of equilibrium where there are no sensor failures due to battery depletion. This work also examines some underlying topologies that guarantee a loop free mobility strategy as well as the network parameters needed to achieve the state of equilibrium.

C. *Contributions*

In this paper we propose a novel approach to energy restoration in WSN by reducing the problem of recharging mobile sensors in a network of arbitrary topology to the implementation of pro-active energy-aware mobility strategies. These mobility strategies are based on a logical Compass Directed Unit sub-graph constructed on top of the original topology. The proposed graph is dynamic, self-correcting and loop free. The major analytical properties of the proposed algorithms such as correctness, termination and guarantee delivery are also discussed.

The proposed strategies for the mobile sensor scenario are validated through a series of simulations, which explore several variables that may impact the performance of the pro-active solutions, such as topology, number of neighbors, size of the network and number of recharging sockets. Consequently, the test results show that all strategies analyzed reached the state of equilibrium. The number of neighbors (node degree) had a positive impact on the cumulative number of sensor losses reported until energy equilibrium is reached. Even the single path approach outperformed the passive solution in terms of cumulative number of sensor losses until equilibrium. Moreover, the experiments show that the closest-first greedy strategy outperforms all others in terms of optimal recharging trips (one hop from recharging station). Finally, even though the passive approach reaches a perfect balanced state (equilibrium without sensor losses); this is achieved using twice the number of recharging sockets when compared to the closest-first pro-active approach.

D. *Related work*

The idea of adding mobility to specific network elements has been previously study as a mechanism to extend a wireless sensor network operating life. In previous studies based on the mobility of certain network components such as [15], [27], [33], [31], more attention has been given to the base stations as a mechanism to balance the energy levels among all sensors but not for network maintenance tasks. In [15] is noted that sensors closer to the base station tend to deplete their batteries much faster than other sensors. These sensors have to route/aggregate data flowing from remote parts of the network towards the base station. This disparity creates bottlenecks in areas closer to the base stations. Luo et. al propose the use of mobile base stations to overcome this limitation. The authors found that for circular deployments, routes that followed the periphery of the circle, combined with short path routing strategies provided the best overall performance. However, their findings will only increase the lifetime but the loss of coverage over time will be inevitable since there are no provisions to recharge or replace sensors in the long run.

For instances where the mobile sensors are responsible for managing their own energy levels and come up with strategies to extent their operating life beyond one battery charge, the standard method to decide when to recharge has been based on fixed thresholds (e.g. [32], [17]). In this case, the service stations take a more passive role and the sensors should be able to compute their remaining operational time and coordinate the use of the service stations [17]. Furthermore, for instances where the sensors or robots have to visit a predefined number of points of interests, [32] describes threshold vs. non threshold-based solutions where robots decide to visit the service stations depending on their proximity and the nature (locations) of the points of interests.

In general, mobility-based solutions to energy management attempt to extend the network lifetime by re-organizing the network components and thus overcoming the disparity in terms on energy degradation. The use of mobile relaying sensors [31] or mobile base stations will help to increase the network operating life but the loss of coverage due to battery depletion will be inevitable since there are no provisions to recharge or replace sensors in a sustainable manner.

Previous work on sensor localization have shown that the distance between nodes can be estimated by the strength of the incoming signal and the relative coordinates can be computed by exchanging this information between neighbors [4]. Also, the sensors could be equipped with a low power GPS receiver to obtain their locations. Therefore, in this work we focus on position based routing strategies as the foundation for our proposed mobility strategies.

Stojmenovic et al.[24] provide a detailed survey of position based routing algorithms. In particular, there are several identifiable properties of the algorithms that are very useful when evaluating their performance. For example: 1) avoiding loops: the algorithm should not rely on timeouts or keeping information on past traffic as a termination mechanism. The algorithms should be loop free, guaranteeing the delivery of the intended packet. 2) Distributed operations: in a localized routing algorithm each node decides where to send a packet based on its local state, its neighbors and the final destination. The objective is to achieve a common goal based on individual efforts without a global knowledge of the network. 3) Single versus multiple path approaches. 4) Routing algorithms use the hop count as the metric to measure effectiveness.

Position based routing algorithms can be divided into progress-based and directional. Examples of progress based algorithm can be found in [28], [18], [25]. The commonality resides in that they try to forward the packet to a neighbor with positive progress towards the final destination. Positive progress is seen as to get closer and closer to the destination every time the packet is forwarded. There are several variants of progress based routing and the main difference resides in the selection of the next hop neighbor. In some cases the selection is random; others attempt to send the packet to the neighbor with the most progress within the transmission range, while others select the closest ones. In the other category we can find the compass routing proposed in [12], where the next sending node uses the location of the intended destination to calculate its direction and selects as next hop the sensor which direction is closer to the destination. However, this approach is not loop-free as shown in [25].

Another possible categorization for routing algorithms deals with the number of path followed. For example, the geographic routing algorithm presented in [11] and the Depth First Search proposed in [26] are examples of single path strategies with guaranteed delivery. Example of stateless algorithms are presented in [3], [5]. In particular, the Face Routing and GFG (Greedy-Face-Greedy) algorithms construct a planar connected sub graph of the Unit graph. To improve performance, the GFG algorithm switches from greedy to face routing on the Gabriel graph if the node fails to find a neighbor closer to the intended destination.

In our particular scenario, we consider the sensors to be static in terms of their sensing requirements. In other words, from the point of view of the application (functional requirements), the sensors are static and placed in a specific set of coordinates. However, they all have the capability of moving if they decide to go to the service station to recharge their batteries. Consequently, the general idea behind our solutions to the network maintenance and energy restoration is to apply concepts of forward progress routing into mobility strategies. Basically, instead of guaranteeing the delivery of a packet to the intended destination, the sensors now use similar routing techniques to create their own itinerary to reach the service stations.

The rest of this paper is organized as follows: Section 2 presents the model. Section 3 examines the proposed passive and pro-active solutions. Section 4 discusses some experimental analysis and Section 5 contains conclusions and discussions on future work.

II. THE MODEL

The proposed mobility-based energy management approach is built within the following theoretical model. The model contains two main components: mobile capable sensors and static recharging facilities. The general requirement for the model is to extend the network operating lifetime by the autonomous recharge of low energy sensors. However, the ultimate goal is to achieve a state of equilibrium where no further sensor losses are reported and accomplish this with the minimum amount of resources. In general, the model includes the following key components:

1) A set of N sensors, $S = \{s_1, ..., s_N\}$ randomly distributed in an area of unspecified shape.
2) A set of static recharge facilities, $F = \{f_1, ..., f_K\}$ also randomly distributed throughout the area.
3) Each facility is equipped with a fixed number of recharging sockets.
4) Facilities and sensors can determine their own positions by using GPS or other localization method.
5) Sensors can communicate with other sensors within their transmission range R.
6) Sensors are static from a functional point of view (application level) but they can move autonomously if needed.
7) All sensors move at the same speed V.
8) All communications are asynchronous. There is no global clock or centralized entity to coordinate communications or actions.

Previous works on energy consumption of wireless sensor networks and protocols such as 802.11, show that the energy required to initiate communication is not negligible. In particular, loss or energy due to retransmissions, collisions and acknowledgments is significant [7], [8]. Therefore, protocols that rely on periodic probe messages and acknowledgments are considered high cost. For these reasons, the design of our mobility solutions and related coordination should be flexible enough to avoid the use of probe messages and complicated state-full protocols. An important goal of our solutions should involve the use dynamic and self-correcting structures and protocols.

It is also noted in the literature that energy consumption of sensors in idle state is as large as the energy used when receiving data [8]. On the other hand, the energy used in transmitting data is between 30-50% more than the energy needed to received a packet. This differences between the energy needed to perform the basic operations are taken into account in our algorithm design and later in the design of our experiments where different cost values are assigned to each operation: idle, send/receive as well as energy used when moving.

III. PASSIVE STRATEGIES FOR MOBILE SENSOR NETWORKS

In this section we attempt to provide the first answer to our initial question: Should the sensors wait or should they act as soon as possible? Let's first start examining the case where the sensors decide to wait. We call this case: a passive strategy. In a passive strategy, the sensors will monitor their energy levels using periodic intervals and after any operation (send/receive, etc.). These intervals do not need to be the same for all sensors nor have they to be synchronized in any way.

The sensors operate in two basic states: BATTERY_OK and BATTERY_LOW. Once the battery levels fall below a pre-defined threshold, which is not necessarily the same for all the sensors and depends on their distance to the station, the sensors will move towards the recharging station. There are two cases two consider:

1) The recharge station is within the sensor's transmission

range and the sensor can send a recharge request right away. 2) The recharging station could be outside the sensor's transmission range and a routing mechanism should be in place to forward the recharge request message to the service station.

Alternatively, the sensor could start its journey towards the recharge station and once it gets there (or at least within range) request an available socket. Regardless of the mechanism chosen, the sensor-facility interactions are implemented based on the service station pattern shown in Figure 1. For simplicity, the pattern shows the case of a service station with only one recharge socket. The recharging process is initiated with a RECHARGE_REQUEST sent by a low battery sensor. The service station will keep a queue of requests received and a ranking based on the sensors energy levels and their distances. When a socket becomes available, the service station sends a RECHARGE_ACCEPT to the smallest ranked sensor. Every time a sensor recharging is completed, the sensor sends a RECHARGE_DONE message to the service station and travels back to its initial position in the network. This process is repeated continuously.

The effectiveness of this method depends on several factors such as: number of sensors in the cluster, distance to the station, number of recharging sockets, etc. Since our ultimate goal is to achieve a point of equilibrium with minimum or not sensor losses at all, a new question arises: will this approach work, and if it does, at what cost? The experimental analysis section provides some of these answers.

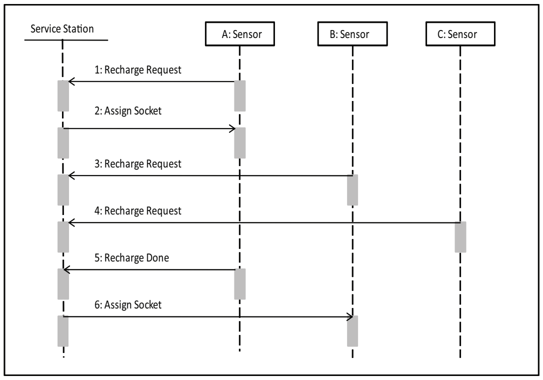

Fig. 1. Design Pattern for a mutex Service Station

It is also important to point out, that when sensors travel to the stations, they create temporary coverage holes. If temporary loss of coverage is an issue of paramount importance for the network, there are solutions to overcome this limitation. For instance, the service stations could be equipped with spare sensors. The number of spare sensors should be equal to the number of recharging sockets and every time a sensor is accepted (a socket becomes available), a spare is dispatched to the sensor's location to take its place. The low battery sensor is now free to travel to the base station and will eventually become a spare after its battery has been recharged.

IV. PRO-ACTIVE STRATEGIES FOR MOBILE SENSOR NETWORKS

In this section we examine the case when mobile sensors decide to act before their batteries reach a critical level and a trip to the recharging station is imminent. The general idea is that sensors will try to get closer to their service stations in order capture the so called "front seats" for when their time comes to make a trip to recharge their batteries. However, the number of front seats is limited (only sensors within one-hop distance to the station) and since the sensors have responsibilities in their corresponding locations, changing locations cannot be a unilateral decision.

In order to minimize coverage holes and coordinate their actions, the sensors will attempt a gradual approach to the service stations by swapping positions with other sensors closer to the recharging station. The concept of energy threshold is still used but to a lesser extent and they are still based on the distance from the sensor to the service station. The operating life of a sensor is now divided in three stages depending on its battery status: 1) a BATTERY_OK or normal operation, 2) SWAPPING_STATE or energy-aware operation and 3) BATTERY_LOW or recharge-required operation. A sensor in a BATTERY_OK state will perform its regular sensing functions as well as accept any swapping proposal from other sensors with less energy. When battery levels fall below a first threshold, the sensor switches its state to a more active SWAPPING_STATE. In this state, the sensor will start its migration towards the service station proposing swapping operations to sensors with higher energy levels. Finally, after falling below a second threshold, a sensor in the BATTERY_LOW state will contact the service station using the station pattern (see Figure 1). Once a socket has been secured, the sensor travels to the station.

The problem is how to find a suitable strategy to reach the recharge station in an effective and timely fashion and achieve this in a distributed manner relaying only of local neighboring information. At this point, we propose to make use of position-based routing strategies. However, instead of sending a packet that needs to be routed until it reaches the intended target, the sensors have to "route themselves" until they reach the service stations. In particular, we propose to reduce the problem of coordinating the recharging of mobile sensors to the problem of finding optimal routes in a logical Compass Directed Unit sub-graph built on top of the original topology. The proposed graph incorporates ideas from forward progress routing techniques, the directionality of compass routing in an energy-aware unit sub-graph.

Routing algorithms use the hop count as the metric to measure effectiveness. In our case, the hop count would be equivalent to the number of swapping operations between sensors in our unit sub-graph. A graph $G = (V, E)$ with vertices $V = \{v_1, ...v_N\}$ and edges $E = \{(v_i, v_j)\}$ with $1 \leq i < j \leq N$ is called a Unit Disk Graph (or Unit Graph) if $d(v_i, v_j) \leq R$ where d is the Euclidean distance between the sensors and R is the transmission range (the same for all sensors). The figure 2 shows an example of the proposed compass directed unit sub-graph.

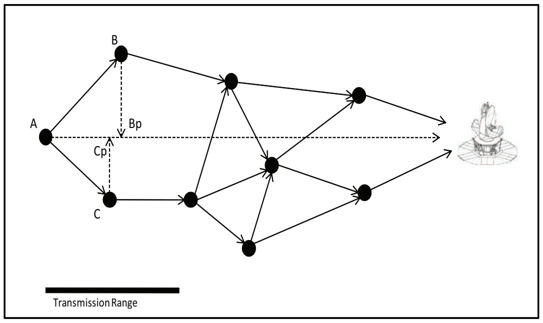

Fig. 2. Compass Directed Unit Graph for Sensor A

When creating the directed graph, a sensor A selects its neighbors based on the following criteria: 1) from all the available sensors within its transmission range, A selects the ones closer the final destination or target. 2) The selected neighbors should provide positive progress. For example, B and C are neighbors of A if the corresponding projections B_p and C_p on the line joining sensor A with the target station, fall within the line segment and not outside. In order to save energy, sensor A will then try to deviate as little as possible from the direction of the target (service station). Therefore, all the sensors that satisfy the conditions 1) and 2) will be ranked according to the following function:

$f(S_i, S_j) = \left\{ d(S_i, S_j) + \frac{d(S_j, S_j p)}{d(S_i, S_j)} \right\}$ where S_i, S_j are the neighbouring sensors, T is the target or service station and $S_j p$ is the projection of S_j on the line segment $S_i T$.

Theorem 1: The mobility strategies based on the Compass Directed Unit Graph are loop free.

Proof: Let $G = (V, E)$ a directed graph with a set of vertices $V = \{S_1, ..., S_N, T\}$ where S_i, $1 \leq i \leq N$ are mobile sensors and T denotes the target, in this case the recharging station. Let E a set of edges of the form $S_i \rightarrow S_j$ where S_j is neighbour of S_i if the following conditions are satisfied: 1) Unit graph criterion: $d(S_i, S_j) \leq R$, where d denotes the Euclidean distance and R is the transmission range. 2) Proximity criterion: $d(S_j, T) < d(S_i, T)$ and $d(S_i, S_j) < d(S_i, T)$ 3) Directionality criterion: $\exists S_j p$ such that $(S_j p - S_j) \cdot (T - S_i) = 0$.

Without loss of generality, we can assume that for any path $P_i =< S_i, ..., S_K, T >$ with $1 \leq i < K \leq N$, the sub-path $< S_i, ..., S_K >$ does not contain any cycles. This claim can be proved by contradiction.

Let us assume for a moment that the algorithm is not loop free. This means that at some point during the execution of the algorithm, a cycle C of arbitrary length K is found. Let $C = \left\{ S_i S_(i+1) ... S_(K-1) \right\} \bigcup \{S_K S_i\}$ with $1 \leq i < K \leq N$. If such cycle C exists, then S_i is neighbor of S_K which means that $d(S_i, T) < d(S_K, T)$. This contradicts the proximity criterion (2). Hence, the Theorem holds. ■

A. Creating the Compass Directed Unit Sub-graph

The active approach to solve the problem of energy management using mobile sensors can be divided into a two stage process. The first part is the construction of the compass directed unit sub graph and the second phase is the swapping state. In the first stage, it is assumed that all sensors have the required levels of energy to construct the graph. The process is rather simple and starts by each sensor sending a broadcast message inviting other sensor to participate. In particular, each sensor will send a NEIGHBOUR_REQUEST message that will be heard by all its immediate neighbors. The only minor twist here is that all the verification of the neighboring criteria takes place at the receiving end. The sensors that satisfied the predefined conditions will reply with a NEIGHBOUR_ACCEPT message, the rest will ignore the request.

It is important to stress that in this algorithm there are no waiting periods, acknowledgments or timeouts for neighbor responses. Since communications are completely asynchronous, a sensor that does not receive any NEIGHBOUR_ACCEPT response assumes that it is located at one-hop distance to the recharging station. For the time being, the sensor will assume that there are no other sensors closer to the station and it will deal with the station directly. This is an important feature of our adaptative discovery algorithm, where if during later phases of the algorithm, a sensor discovers another sensor which should be its neighbor or parent, the necessary updates take place and the graph is reconfigured dynamically. The next section discusses in more detail several scenarios where this or similar situations occur.

At the end of this phase each sensor will have two routing tables: one containing its neighbors (sensors from which NEIGHBOURS_ACCEPT messages were received) with their corresponding ranking and other table containing all its parents (sensors to which NEIGHBOUR_ACCEPT messages were sent). The algorithm 1 summarizes the behavior of the sensors during this process. The service stations have no involvement at this time. The functions $DistancePointToLine$ and $DistancePointToLineIn$ compute the distance between the potential neighbor and the line segment joining the sensor and the service facility. If the projection falls inside the segment, the function $DistancePointToLineIn$ returns true, otherwise it returns false.

B. The Swapping Stage

The second stage of the active approach to sensor recharging is called the "swapping stage". This phase starts when sensors change their state from BATTERY_OK to SWAPPING_STATE as a result of their battery levels falling below a first threshold. Once a sensor enters the swapping mode, it will try to get closer to the base station by making a series of one-hop swaps with its neighbors. If there are no neighbors, either because the sensor is within one-hop of the station or it has not found out about any neighbors yet, the sensor just waits since its battery is still fully operational. Only when it changes to BATTERY_LOW state, the sensors will attempt to contact the recharge station (defaults to the passive approach).

Algorithm 1 Graph Construction: sensor S and facility F

```
(* In State $INIT$ : *)
begin
send $NEIGHBOUR\_REQUEST$ broadcast message
become $BATTERY\_OK$
end
(* In State $BATTERY\_OK$ : *)
begin
if receiving $NEIGHBOUR\_REQUEST$ from S' then
    if $d(S,F) < d(S',F)$ and $DistancePointToLineIn(S,S',F,distanceToLine)$ then
        parentList.Add(S')
        send $NEIGHBOUR\_ACCEPT$ to S'
    end if
end if
if receiving $NEIGHBOUR\_ACCEPT$ from S' then
    $rankingParameter = d(S,S') + DistancePointToLine(S,S',F)/d(S,S')$
    $neighbourList.Add(S', rankingParameter)$
    neighbourList.rank()
end if
end
```

The swapping operation is initiated with a sensor sending a SWAP_REQUEST message to its lowest ranked neighbor. Neighbors could be ranked based on their distance (closest to farthest) and their direction relative to the target station. Another option of ranking includes the energy levels of neighbors as a metric as well as the number of 2-hop neighbors (number of neighbors of my neighbors). If the current energy level of the neighbor is larger than the parent sensor, the neighbor replies with a SWAP_ACCEPT message and travels to the position of the parent sensor. If its energy level is lower, the neighbor replies with a SWAP_DENY message. Once a requesting sensor has initiated the swapping process it will not entertain any SWAP_REQUEST messages until the swapping operation is completed. The swapping operation is considered atomic and once completed both sensors will send a SWAP_COMPLETE message that will be used by current and new neighbors/parents to update their routing tables.

It is important to mention that sensors in the SWAP_STATE will still accept to swap positions with other sensors farther from the station (with less energy) even though this temporary backwards movement could be seen as a small setback. Early experimental tests with sensors in the SWAPPING_STATE rejecting all swapping requests from their parents proved to be too restrictive. In other words, sensors were very reluctant to make temporary backwards movements as they all attempted to move forward. As the overall energy levels of the network decrease and due to the random distribution of energy among the sensors, sensors with lower energy levels were prevented from making progress towards the station once all their neighbors were in swapping mode even when their energy levels where higher than their parents. Consequently, by accepting a swap request at any stage other than the BATTERY_LOW state, a sensor can be temporarily delayed in its quest for the recharge station but this small step back is rewarded by a more balanced overall performance.

The final step of this phase takes place when battery levels falls enough to trigger a change to the BATTERY_LOW state. In this state, the sensors behave exactly as in the passive approach and their interaction with the service station is defined by the pattern discussed earlier. A battery-low sensor sends a RECHARGE_REQUEST message to the recharge station and waits until an available socket is assigned. When this occurs, the sensor will receive a RECHARGE_ACCEPT message from the station and will initiate its journey. In an ideal system, all sensors will reach the BATTERY_LOW when they are exactly at one-hop distance from the service station. When the trip to the recharge station is made from a one-hop position (there are no neighbors), we call this "One-hop run" or "Optimal run". Contrarily, if the trip is made from any other location, it is called a "panic run"'. We will come back to visit this issue when we discuss the experimental analysis of the different strategies.

C. Properties

The figure 3 shows two common swapping scenarios that are useful to demonstrate an important property of the swapping algorithm: it is self corrected. For example: the left side shows two concurrent swapping operations between sensor $S2 \leftrightarrow S3$ and $S4 \leftrightarrow S5$ respectively. As part of the swapping process, the sensors involved exchange their routing information, that is, their corresponding neighbor and parent tables. However, since multiple swapping operation may occur at the same time (like in this case), when sensor S2 finally arrives to the position occupied by S3, it believes (according to its routing table) that S4 is one of its neighbors. However, this is no longer the case since S4 has switched positions with S5.

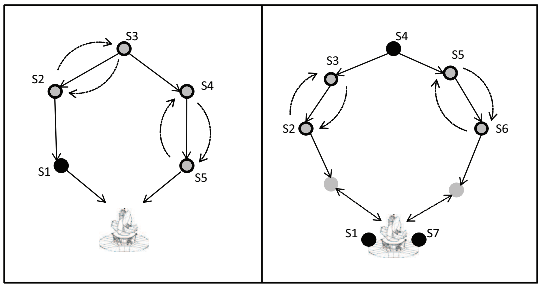

Fig. 3. Two common swapping scenarios

The other situation takes place when a sensor finally makes a trip to the recharge station. The right side of figure 3 depicts the case when two sensors S1 and S7 are being recharged simultaneously. While this process takes place, sensors S2 and S3 in one side and sensors S5 and S6 are swapping positions. Once the recharging process is finished, sensors S1 and S7 return to their last known position. However, the structure of the network around them has changed. This situation is even more evident when trips to the service station are made from distances of more than one hop as a result of what we call a panic run.

The solution to these problems is to switch from an Id-based system to a position-based system, where the important factor is the relative position of your neighbors and not their corresponding Ids. In short, the routing tables are just partial maps of the network indicating the position of the neighbors and parents. But the information of the actual sensors occupying the positions is secondary. In other words, a sensor knows that at any given point in time it has n neighbors at the positions $(x_1, y_1)...(x_n, y_n)$ and p parents at positions $(x'_1, y'_1)...(x'_p, y'_p)$. This information is static and will not be modified. The only possible change is the addition of a newly discovered neighbor or parent sensor. However, the identity of the sensors occupying the positions is dynamic and will get updated every time a swapping operation occurs. The mechanism to detect changes in the routing tables is triggered by sending a SWAP_COMPLETE message. When two neighboring sensors successfully complete a swapping operation, they will announce their new positions by sending a SWAP_COMPLETE messages. Sensors within the transmission rage that listen to this message will verify whether any of the positions involved in the exchange belongs to their routing tables and update the appropriate entry with the new occupant of that position.

On the other hand, a sensor returning from the service station needs to re-discover the new occupants of its routing tables. This process is initiated by a SENSOR_RECHARGED message sent by the newly recharged sensor as soon it reaches its last known position on the network. Potential neighbors and parents, upon receiving this message will reply with NEIGHBOUR_UPDATES and PARENT_UPTADE messages accordingly. This process is also used for parent to update their information about the energy levels of this newly recharged neighbor.

V. EXPERIMENTAL ANALYSIS

This section examines the simulation results for the passive and active strategies described in the previous section. For all test cases the simulation software utilized was Omnet++ [30] along with the mobility framework extension [6]. For all the experiments, the sensors and facilities are randomly placed in an area of 1000x1000m^2. Service facilities are static and once placed cannot be relocated but sensors are mobile, although their movements are governed by the mobility strategy followed. The analysis centers on three important aspects of the solutions:

1) Whether or not a state of equilibrium is achieved and the number of failures until such condition is met.
2) The quality of the strategy measured in terms of optimal runs vs. panic runs.
3) The resources required to achieve a perfect state of equilibrium.

The test cases presented in the next section are designed to measure the performance of the algorithms for each particular case. For all cases, constant cost values were assigned to each basic operation, send, receive, idle and each unit of distance traveled. The relationship between these values follows some of the experiences found in the literature [7], [8]. The sensors will check their battery status at periodic intervals and after an event has occured (e.g. a new message is received, etc.). The intervals are chosen randomly and simulate the sleep-idle-active cycle normally followed by the sensors. Every time the battery is checked the levels are decreased by a predefined constant. This particular behavior simulates the energy consumption in the idle state. The energy used when receiving information will be 50% less that the energy required to send a message and the energy levels for each sensor will be decreased for each unit of distance (e.g. meters) traveled. The focus of the experiments is not to measure the energy consumption in each operational state but to establish similar parameters to evaluate and compare the performance among the proposed strategies.

A. Sensor losses over Time

The first test case attempts to find out whether the active solution reaches a state of equilibrium. In other words, measure the number of failures (total sensor losses due to battery depletion) over time until the system reaches a state where no more failures are reported. We call this state: the state of equilibrium. In particular, several active strategies are examined: 1) the closet first strategy, where sensors attempt to make forward progress by swapping positions with the closest neighbor. 2) Variable degree, where the number of neighbors is restricted and an upper bound for the graph degree is set from single path (degree 1) until degree 4. The neighbor selection is similar to the closest first but establishing an upper bound. (i.e. the closest, the first and second closest, and so on) And finally 3) the closest-with-most-energy first where the sensor selects the swapping partner based on the distance/energy ratio of its neighbors.

The figure 4 shows the result of an experiment involving 100 sensors and one service facility deployed in an area of $1000x1000m^2$. The facility is equipped with two sockets which allow two sensors to be recharged at the same time. The experiments are run for 10^6 simulation seconds. Confirming our expectations, all the variations of the pro-active approach reach the state of equilibrium. This is a positive result which means that all the energy spent during the graph creation, swapping and graph reconfiguration in a network with a 100:1 sensor-facility ratio with only two sockets, does not overwhelm the system to the point of preventing it from reaching equilibrium.

Another interesting result is that graph degree has a positive impact in the performance of the algorithms. Multiple path approaches outperform single path strategies even when the number of control messages and network maintenance required is higher. The closest-first appears to be the best

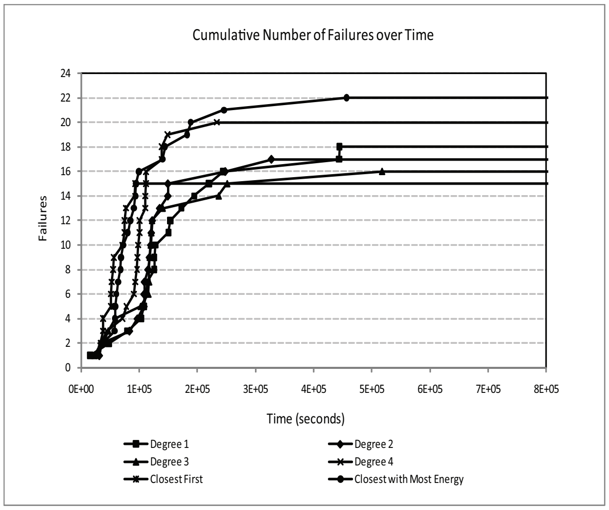

Fig. 4. Failures over time for active strategies.

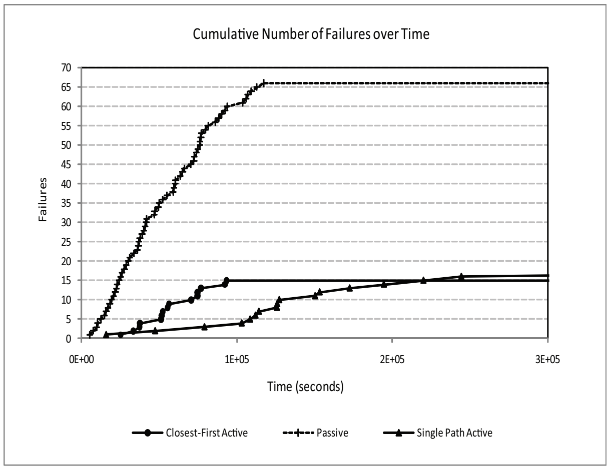

Fig. 5. Passive Strategy vs. Active Strategies

performer of the group. It is important to mention that the closes first approach incorporates the directionality factor in the ranking which differs from the distance-based closet first forward progress routing strategy. Another interesting observation is that the closest-with-most-energy-first approach does not provide the best performance, contrary to what we may have anticipated. The idea of adding the energy level in the ranking did not report great improvements. A possible reason for this is that neighbors with higher energy levels were favored over others closer in directionality but with relative lower energy levels.

The next logical question could be: how do active strategies perform when compared to a passive approach? The second part of this test (seen in figure 5) addresses this issue by comparing two active strategies: closest-first and the single path strategy, with the passive approach. Surprisingly, even the single path active strategy outperforms the passive approach by a significant margin. Even though the passive strategy reaches the state of equilibrium faster than the single-path active strategy, it does so at a very high cost (in terms of sensor losses). This result implies that for high sensor-facility ratio deployments the number of sockets assigned to the recharge station is this experiment is too restrictive.

B. Quality of the Solution

The second test case is designed to verify the quality of the active solutions. In an ideal system, sensors following the active strategies should reach the state of equilibrium using “One-hop runs” only. The “Panic runs” occur when the sensors cannot get closer to the service stations because all their neighbors have lower energy levels. This test examines the breakdown between “One-hop runs” and “Panic runs” for all the active solutions. The characteristics of the network are the same as the previous test case and the experiments are executed the same length of time (10^6 simulation seconds). The Figure 6 shows the percentage of one-hop and panic runs out of the total number of recharging trips. As expected, the degree of the graph has a positive impact on the quality of the solution. As the node degree increases, there are more alternative paths to arrive to the service station and ultimately more “front seats” available. The closet-first approach (which has no limitation on the number of neighbors within range) is once again the best performer among all the strategies, with 40% of all the trips, being “Optimal runs”.

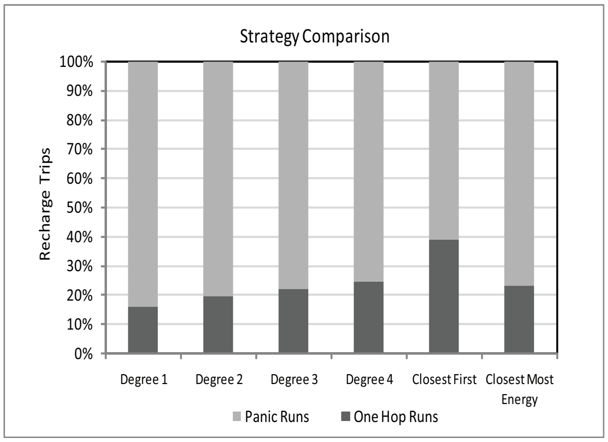

Fig. 6. One-hop runs vs. Panic runs.

This experiment exposes an interesting property of the network and the location of the recharge station. For all the experiments, the services station was located at the center of the area. The density of the graph around the service station in conjunction with a multiple path, unrestricted degree strategy such as closest-first should yield the best results. To maximize the number of sensors within one-hop distance to recharging station, the stations could be deployed in the denser areas of the network. On the other hand, from a practical point of view an approach that reaches perfect state of equilibrium faster and with fewer resources, should be preferred regardless of the breakdown between optimal and “panic runs”.

C. Achieving Perfect Equilibrium

The last test case attempts to find out the resources needed to achieve a perfect state of equilibrium. This means that there are no reported failures in the network due to the depletion of the sensors' batteries. To illustrate the experiment, the best pro-active approach (closest first) is selected and compared to the passive solution. The experiment involves a series of simulations in a network with 100 sensors and 1 service station but varying the number of sockets. Figure 7 shows the comparison between the two solutions and plots the impact of the number of recharging sockets on the total number of failures (sensor losses) until equilibrium.

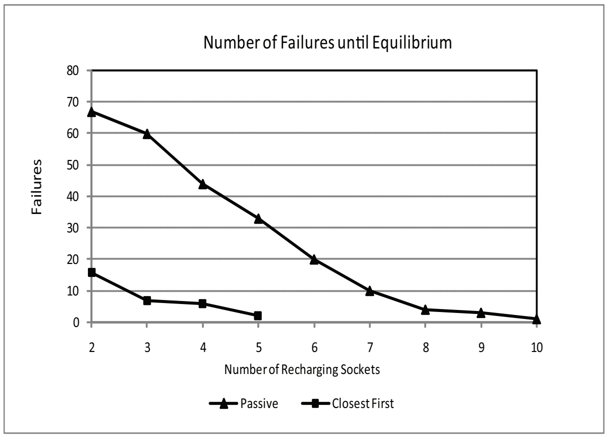

Fig. 7. Failures until Equilibrium by number of Recharging Sockets

A positive and expected result of this experiment is that both approaches reached the state of perfect equilibrium at some point. The main different though, is that passive approach needed twice as many sockets to eliminate all failures. On a positive note, the progression for the passive approach is rather fast considering the high number of failures with only two sockets.

VI. CONCLUSIONS AND FUTURE WORK

The results presented in this work mark our first steps to address the emerging and challenging problem of energy management and restoration in a mobile sensor network scenario. In particular, for networks with mobile sensors and static service facilities where sensors can visit the facilities to recharge their batteries. However, the facility resources (recharging sockets) are limited and sensors should coordinate their actions to access this shared resources efficiently. Existing energy management approaches are mainly based on fixed threshold as the deciding factor in the strategy to follow. Under these circumstances, the problem is: Should the sensors wait until their batteries fall below the thresholds or should they take a more pro-active approach while they are fully operational? This work provided some answers to these issues by comparing passive vs. pro-active approaches to energy management based on different mobility strategies.

Our solutions recommend taking a pro-active approach to energy restoration based on several mobility strategies. As the foundation for their mobility strategies, sensors create a logical compass directed unit graph. In particular, we propose to reduce the problem of coordinating the recharging of mobile sensors to the problem of finding optimal routes in a logical Compass Directed Unit sub graph built on top of the original topology. The proposed graph incorporates ideas from forward progress routing techniques, and the directionality of compass routing in an energy-aware unit sub-graph. The idea behind each mobility strategy is that sensors will swap positions with graph neighbors with higher energy levels and thus get closer to the service station. The mobility modes are built upon routing concepts but instead of sending packets, sensors navigate on the logical graph until they reach the target destination.

In summary, the proposed pro-active solutions have the following properties:

1) The proposed graph topology guarantees that any node reaches the service facilities in a finite number of swapping operations. The trajectory is loop-free.
2) All decisions made by the sensors regarding the next swapping operation are based on local knowledge (the algorithms are completely distributed and localized)
3) The proposed underlying topology is position-based. The sensors create a network map with the positions of their immediate neighbors and parents.
4) The proposed graph is dynamic and self-correcting: new sensors can be added or deleted at any time and new neighbors are re-discovered any time a successful swapping or recharge operation takes place.

Any successful energy management strategy must reach a state of equilibrium, where no further sensor losses are reported and sensor cooperates to share a common recourse (recharge station). To measure the quality of the solutions we centered our analysis on several key indicators, such as: number of sensor failures or sensor losses until equilibrium, distance traveled to reach the service station (optimal runs vs. panic runs) and resources needed to achieve a perfect equilibrium (no failures due to battery depletion).

In summary, the experimental analysis show the following results:

1) All the variations of the pro-active approach (closest-first, variable degree, closest-with-most energy) reached the state of equilibrium.
2) The closest-first active strategy outperformed all other pro-active strategies.
3) Even the worst performer among the pro-active strategies (single path) outperforms the passive approach.
4) The closest-first strategy provides the most balanced solution, where 40% of the recharge trips are initiated from a one-hop distance to the service station.
5) All active solutions reach the state of perfect equilibrium by increasing the number of recharging sockets assigned to the facilities. However, the passive solutions needs twice as many sockets when compared to the closest-first active strategy.

Future enhancements to this work may involve the study of the proposed pro-active strategies under the following scenarios:
1) Variable transmission range values. These scenarios will help study the impact of sensor technology and protocols (e.g. 802.11, 802.15.4, etc.) and their direct impact on the neighbor selection process.
2) Validate the proposed pro-active strategies under various cost measures. For example, the cost of physically moving a sensor certain distance is much higher than the corresponding radio transmission over the same distance. Therefore, assigning different relative cost values to each unit of distance travel would help determine the limits of the proposed pro-active strategies.
3) New underlying topologies based on different neighbor selection process.
4) Adding information about the energy levels of the 2-hop distance neighbors and modify the proposed strategies accordingly. A generalization of this approach would be the calculation of the most energy efficient directional path to reach the recharging station.

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